Section 6

ALI Silicon Carbide (SiC) Technology

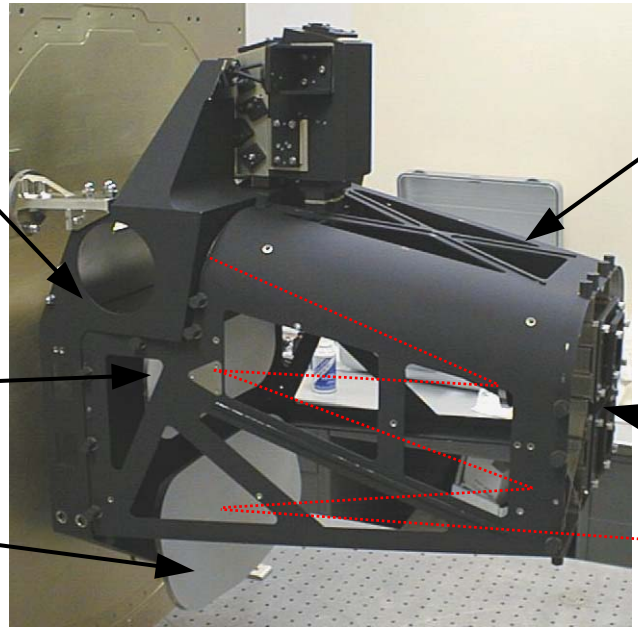
. . . J. Robichaud

SSG Precision Optronics, Inc.

Introduction

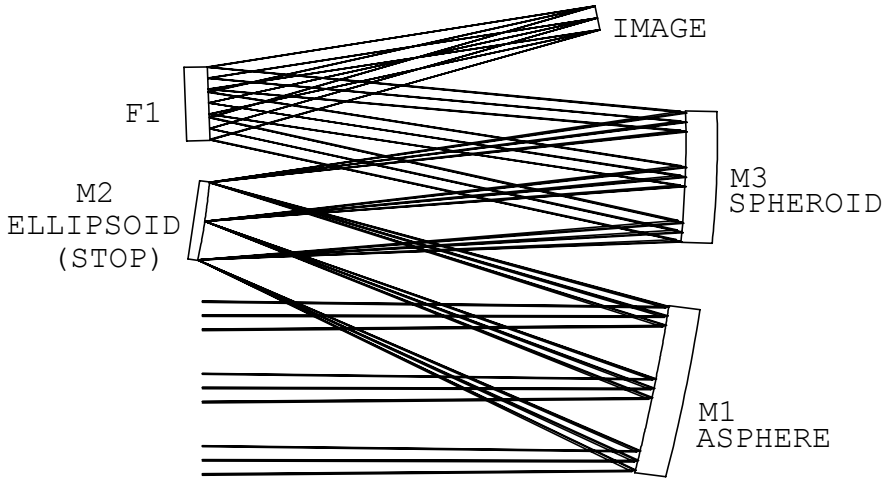
- ***SSG Precision Optronics Background***
  - ***20+ year old small business***
  - ***Specializes in the design, fabrication, and test of all-reflective telescope systems for space applications***
  - ***30+ space systems developed and delivered***
  - ***10+ years of experience with SiC materials and SiC instruments***
- ***SSG NMP EO-1 Mission Contributions***
  - ***Partner in NMP IPDT***
  - ***ALI optical design, fabrication and test support to MIT/LL***
  - ***Incorporate SiC technology into ALI instrument***
  - ***SSG also responsible for design, fabrication and test of Hyperion optical system in support to TRW***

ALI Instrument Overview



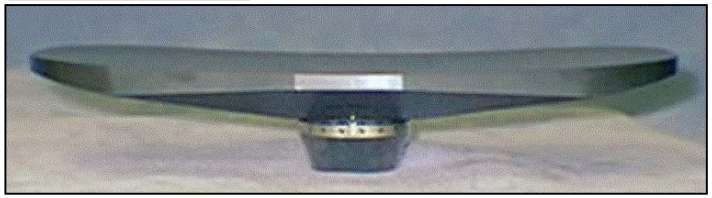
- ***Primary Telescope Specifications***
  - *Aperture: 12.5 cm*
  - *Focal Length: 94 cm*
  - *Field of View: 1.0 x 15 degrees*
  - *Wavelength: 0.4 - 2.5 μm*
  - *MTF @ 0.6 μm (37.5 lp/mm): > 0.5*
  - *Distortion: < 275 μm; < 250 μm*
- ***Primary Design Elements***
  - *4 mirror, all reflective, unobscured optical design*
  - *Flat focal surface*
  - *Hot Pressed SiC optics*
  - *Invar 36 metering structure*

ALI Optical Design



ALI Raytrace

ALI Secondary Mirror

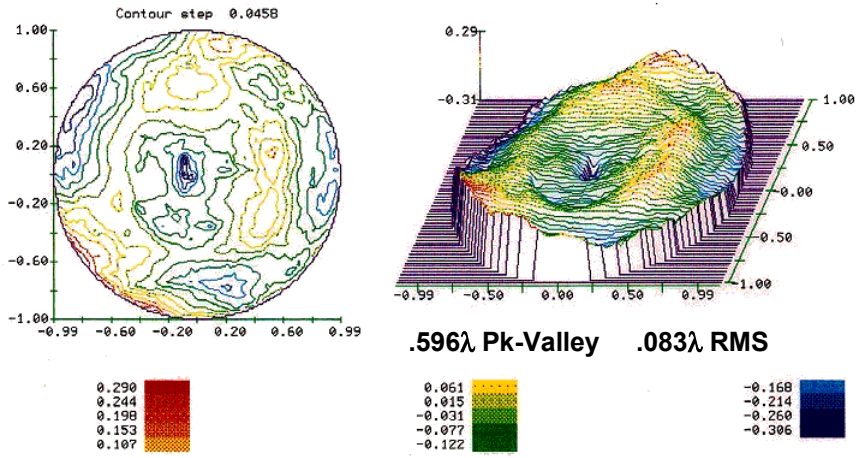


ALI Primary Mirror

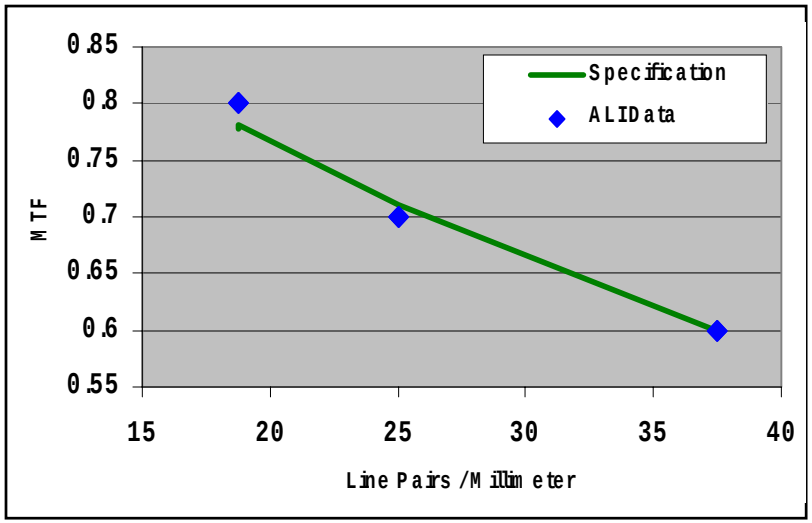
- ***Optical Design***
  - ***Reflective version of Cooke Triplet***
  - ***Aperture stop on secondary mirror***
  - ***Off-axis, wide field of view***
  - ***Flat image plane***
- ***ALI Mirrors***

	Primary	Secondary	Tertiary	Fold Flat
Optical Shape	General Asphere	Ellipsoid	Sphere	Flat
Size	13.1" x 6.6"	3" diameter	11.7" x 5.3"	10.8" x 3.4"
Material	Si on SiC	Si on SiC	SiC	SiC
Base Radius	-65.5"	23.7"	-36.6"	NA

ALI Optical Performance (Image Quality)



On Axis, system level Wavefront Error (WFE)



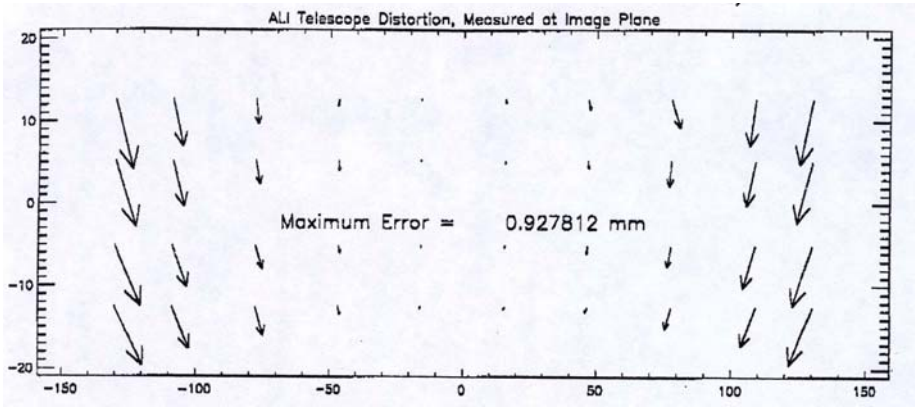
MTF spec and performance

- ***System Level Wavefront Error***
  - ***WFE derived from MTF specification using Code V***
  - ***Required system WFE (@ temp) < 0.15 λ RMS (@ 0.63 μm)***
  - ***12 Field points tested, System WFE (@ temp) 0.089 - 0.148 λ RMS (@ 0.63 μm)***

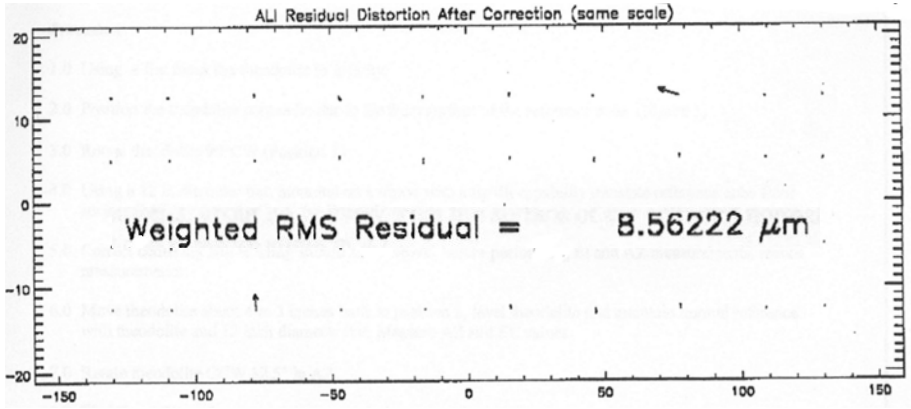
- ***System Level MTF***
  - ***MTF performance projected from wavefront maps input specification using Code V***
  - ***System meets or exceeds spec at 18.75 and 37.5 lp/mm***

ALI Optical Performance (Distortion)

- ***Optical Distortion***
  - ***Distortion measured by mapping the angular locations of 40 points on a scribed target through the ALI optical system***
  - ***Uncorrected data shows maximum distortion vector length of 928 μm***
  - ***Cubic polynomial data correction (Dr. David Hearn, MIT/LL) brings residual distortion values down below 9 μm***



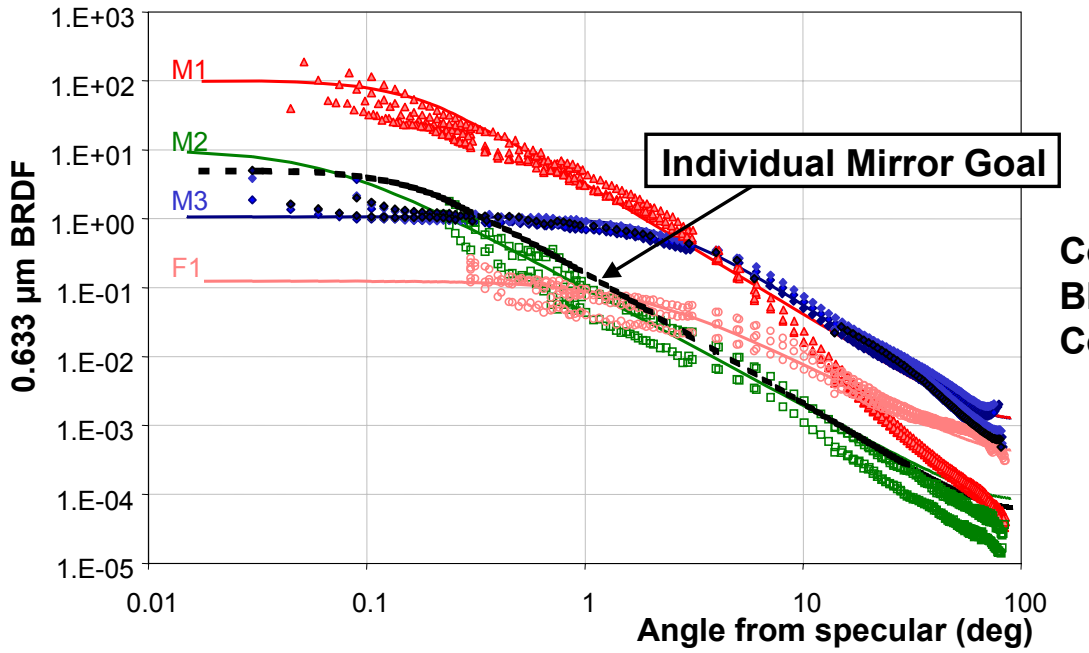
Distortion Map Prior to Correction



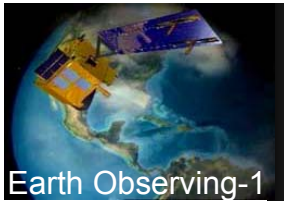
Distortion Map After Correction

ALI Optical Performance (Stray Light)

- ***Stray Light***
  - ***ALI Flight optics do not meet ALI stray light requirements for 5 of the 8 spectral wavebands (Lambda Research)***
    - *Bands out of spec by 2x - 10x*
  - ***System level stray light requirement has been converted to component level BRDF requirements (Lambda Research)***
  - ***BRDF needs 20x improvement (ALI M1) to meet stray light requirements***

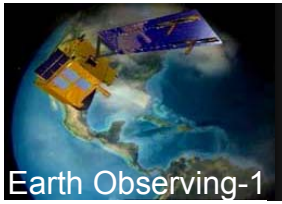


Component BRDF Comparison



ALI Performance Summary

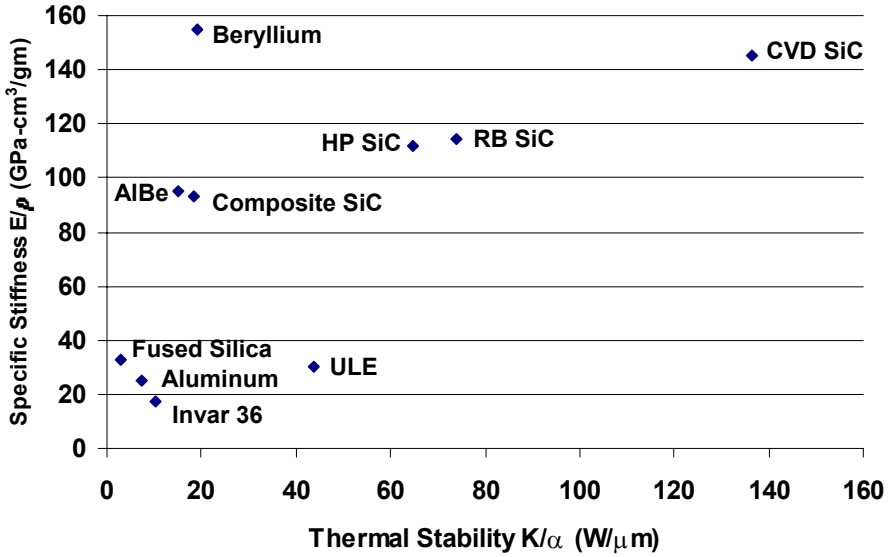
- ***ALI SiC optical system meets or exceeds most of the telescope requirements***
  - ***Component level surface figure***
  - ***Reflectivity***
  - ***Field of view***
  - ***Angular resolution***
  - ***Point spread function***
  - ***System throughput***
  - ***Image quality over FOV***
  - ***Distortion map over FOV***
  - ***Focal length***
  - ***Aperture uniformity***
  - ***Mechanical stability***
  - ***Thermal stability***
  - ***Size***
  - ***Weight***
- ***The one exception noted is the system stray light performance of the system, component level BRDF of SiC optics***
  - ***NASA funded technology program has been completed at SSG in order to demonstrate that this limitation, associated with these specific flight optics, is not a fundamental limitation associated with SiC optics technology***

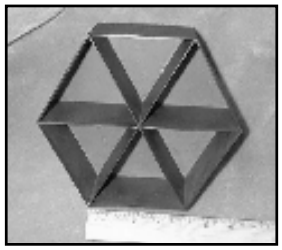


Technology Description

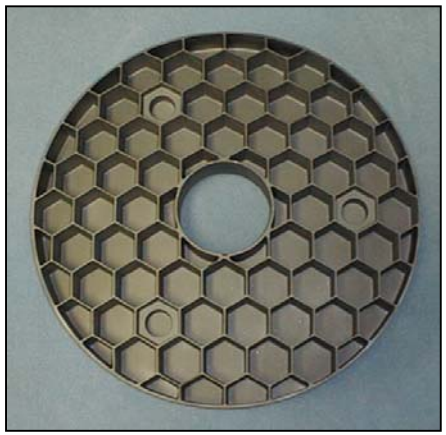
- ***Optical Design***
  - ***Wide field of view***
  - ***Flat image plane***
  - ***Low distortion***
  - ***Excellent image quality***
- ***SiC Materials Technology***
  - ***Hot Pressed SiC Optics***
  - ***Polished SiC flat and spherical surfaces***
  - ***Polished, Silicon coated SiC aspheric surfaces***
  - ***Protected silver coatings***

SiC Materials Advantages





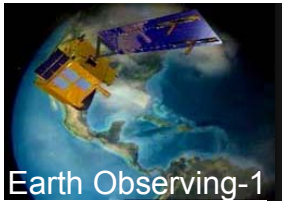
RB SiC Mirror Substrates (as cast)



- ***Different forms of SiC suitable for different applications***
  - ***Specific Stiffness of SiC (HP, RB, CVD) 70% - 90% of Beryllium***
  - ***Thermal Stability of SiC 3x - 1.5x better than ULE glass***
  - ***Hot Pressed SiC suitable for simple "slab"-type geometries***
  - ***Reaction Bonded SiC produces rib-supported, lightweighted mirrors without any costly ceramic machining steps***

ALI SiC Description

- ***Hot Pressed SiC Optics***
  - ***HP SiC has flight heritage through NMP DS-1 MICAS payload***
  - ***Spherical and flat surfaces polished directly in SiC material***
  - ***Aspheric surfaces produced in a silicon cladding over SiC mirror substrate***
  - ***Moderate mirror lightweighting***
  - ***Denton protected silver on all optics***
- ***Invar 36 Metering Structure - Optical Bench***
  - ***Invar selected to avoid brittle damage risks associated with conventional SiC materials***
  - ***Composite SiC technology not deemed sufficiently mature***
  - ***Aggressively lightweighted Invar structure provides structural stability and good CTE match to SiC optics***
    - *MIT/LL machine shop responsible for bench fabrication*



EO-1 Technology Program

- ***Technology program funded by NASA, augmented with SSG internal R&D efforts***
- ***Three main objectives***
  - ***Demonstrate bare SiC (flat), and silicon coated SiC (aspheric) optics with finish/scatter suitable for future ALI-like missions***
  - ***Better quantify the effects of Denton silver coating on SiC optics scatter performance***
  - ***Incorporate current state-of-the-technology SiC materials into the technology program (RB SiC mirror substrates)***
- ***A number of witness samples and small aspheric optics produced in order to facilitate coating and polishing process optimization***
  - ***Results of these process optimizations applied to the spare ALI primary mirror in order to demonstrate this improved result on a representative, flight-like mirror***

Process Optimization Samples

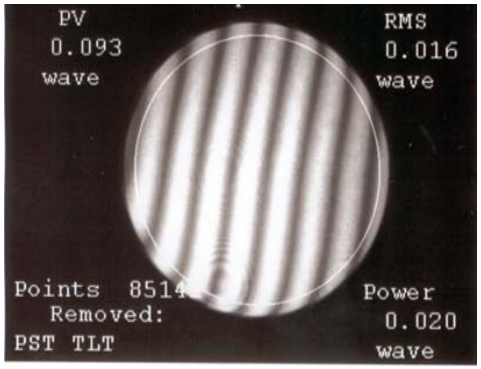
- ***Numerous process optimization samples produced***
  - ***RB SiC flats***
    - *2" diameter*
  - ***Silicon coated RB SiC Aspheres***
    - *Convex hyperboloid (3" diameter)*
    - *Concave ellipsoid (4" diameter), rib supported*
    - ***Spare ALI Primary Mirror***
- ***Data collected***
  - ***Surface figure***
  - ***Surface roughness (before and after Denton Silver)***
  - ***BRDF (before and after Denton Silver)***

Spare ALI Primary Mirror (Concave Asphere)

Concave Ellipsoid

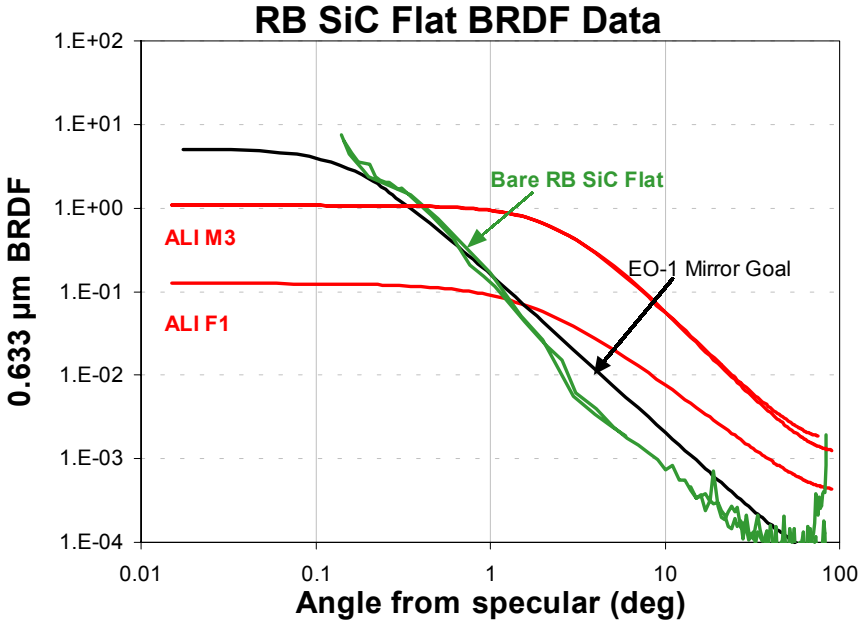
Convex Hyperboloid

RB SiC Flat Sample Results



RB SiC flat surface figure

- **0.016 λ RMS**
- **0.093 λ Pk-valley**



◆ *Surface Figure - Finish*

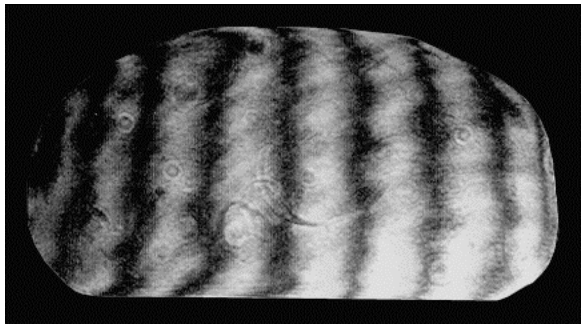
	Sample #1	Sample #2
Surface Figure	0.016 λ RMS (@ 0.6 µm)	0.016 λ RMS (@ 0.6 µm)
Surface Roughness (prior to Denton coating)	7.18 Angstroms RMS	8.14 Angstroms RMS
Surface Roughness (after Denton coating)	7.30 Angstroms RMS	7.58 Angstroms RMS

◆ *Surface Scatter - BRDF*

- ***RB SiC samples shows dramatic improvement in scatter compared to ALI flight optics meeting EO-1 ALI specifications***

SSG
Precision Optronics, Inc.

Silicon Coated SiC Asphere Sample Results



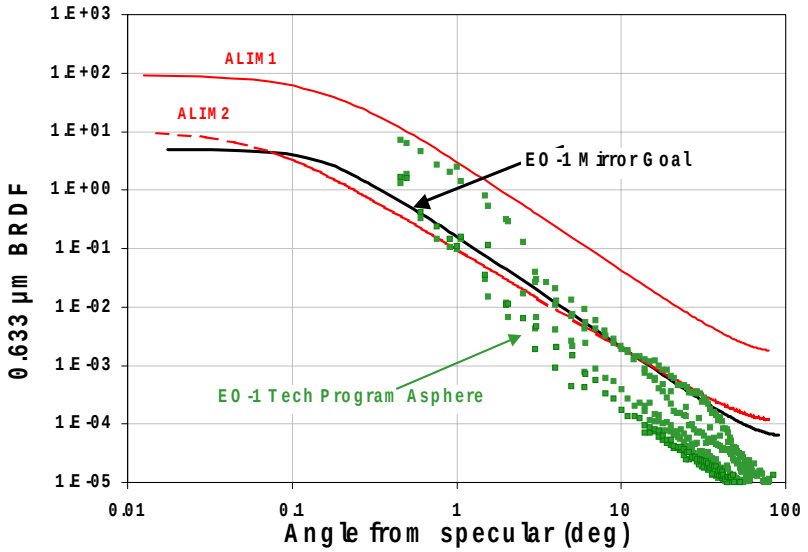
Spare ALI Primary Mirror surface figure

- 0.035 λ RMS
- 0.294 λ Pk-valley

Surface Figure - Finish

	Cvx Hyper	Ccv Ellips
Surface Figure	0.035 λ RMS (@ 0.6 μm)	0.035 λ RMS (@ 0.6 μm)
Surface Roughness (prior to Denton coating)	27.0 Angstroms RMS	10 Angstroms RMS
Surface Roughness (after Denton coating)	28.6 Angstroms RMS	TBD

Si coated SiC Asphere BRDF Data



Surface Scatter - BRDF

- *Si coated SiC samples show improved scatter, all BRDF measurements (with the exception of one close angle data set from one test point) meet ALI specs*

Summary

- ***ALI SiC flight instrument demonstrates excellent image quality, MTF, and distortion performance over a wide field of view***
- ***SSG's continuing SiC materials development allows new SiC materials to be applied to similar missions***
  - ***Significant cost savings***
  - ***Significant weight savings***
  - ***Improved material properties***
- ***EO-1 Technology Program has demonstrated RB SiC flats and silicon coated RB SiC aspheres which meet or exceed BRDF-stray light requirements associated with next generation ALI-like missions***
  - ***Stray light - scatter performance demonstrated on spare ALI primary mirror with excellent results***